A TUTORIAL ON DATUMS
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As a general definition, a datum is any quantity or set of quantities that may serve as a referent or basis for calculation of other quantities. This broad characterization, in turn, leads to two related definitions of a geodetic datum.

> A geodetic datum is a set of constants specifying the coordinate system used for geodetic control.
>
> A geodetic datum is as defined above, together with the coordinate system and the set of all points and lines whose coordinates, lengths, and directions have been determined by measurement and calculation.

The first definition is realized, for example, by specification of an ellipsoid and associated origin and orientation information. The second definition, which is prevalent in mapping and charting, is realized, for example, by specification of ellipsoid, origin, and orientation in combination with a self-consistent set of observed reference coordinates. The first definition represents an *idealization* of a geodetic datum, and the second definition expresses the *realization* of a geodetic datum.

Before the advent of manmade satellites, geodetic positions in surveying were determined separately, either horizontally in two-dimensions as latitudes and longitudes or vertically in the third dimension as heights or depths.

Horizontal datums have been defined using a reference ellipsoid and six topocentric parameters expressing origin, and orientation. One example North American Datum (NAD) 1927. Due to the constraints and requirements of the times, horizontal datums were non-geocentric in definition.

Vertical datums are expressed in some form of orthometric height, and can be clustered into two categories: those generally based on Mean Sea Level (MSL), and those based on some tidally-derived surface of an averaged high or low water. Examples of the former is the North American Vertical Datum (NAVD) 1988, and an example of the latter is Mean Lower Low Water (MLLW). Vertical datums depend upon two elements, the approximation or realization of Mean Sea Level, and the approximation or realization of orthometric height.

Three dimensional datums are defined using a reference ellipsoid and six geocentric parameters expressing origin, and orientation. Unlike a horizontal datum, a three dimensional datum provides the foundation for accurate determination of ellipsoid heights. Examples of three dimensional datums are North American Datum (NAD) 1983 and World Geodetic System (WGS) 1984.

The North American Datum 1983 (NAD 83) was affirmed as the official horizontal datum for the United States by a notice in the Federal Register (Vol. 54, No. 113 page 25318) on June 14, 1989.

The North American Vertical Datum 1988 (NAVD 88) was affirmed as the official vertical datum for the United States by a notice in the Federal Register (Vol. 58, No. 120 page 34245) on June 24, 1993.

Geodetic Reference Systems and Reference Frames
Using the satellites orbiting around the Earth, the determination of geodetic positions became three-dimensional, either as rectangular (X, Y, Z) coordinates or converted to geodetic (latitude, longitude, ellipsoidal height) coordinates using an Earth-centered ellipsoid. Because of this methodology, it became possible to establish positions of high accuracy in a rectangular reference frame without specification of an ellipsoid. An example of such a reference frame is the International Terrestrial Reference Frame (ITRF) 1997. A geodetic reference system is the combination of a reference frame and an ellipsoid. As seen above, a geodetic reference system is a synonym for a three dimensional datum. Examples of geodetic reference system are North American Datum 1983 and World Geodetic System 1984. When the

International Terrestrial Reference Frame (ITRF) is specified in combination with a geocentric ellipsoid, such as the Geodetic Reference System (GRS) 1980 ellipsoid, then it is also a geodetic reference system.

The geodetic reference system used by unaugmented GPS is the WGS 84. The most recent WGS 84 (G873) reference frame and the ITRF94 system are in agreement to better than ten centimeters.

The geodetic reference system used by deployed GPS augmentations (the Maritime Differential GPS and the Nationwide Differential GPS (NDGPS)) is the NAD 83. The DGPS corrections provided by these augmentations are referenced to NAD 83, thus allowing DGPS receivers to easily provide NAD 83 coordinates. The National Continuously Operating Reference Station (National CORS) system includes coordinate data bases in both the NAD 83 geodetic reference system, and in the ITRF97 reference frame combined with the Geodetic Reference System (GRS) 1980 ellipsoid.

Geoid

The geoid is a specified equipotential surface, defined in the Earth's gravity field, which best fits, in a least squares sense, global mean sea level. It should be noted that due to effects such as atmospheric pressure, temperature, prevailing winds and currents, and salinity variations, MSL will depart from an equipotential surface by a meter or more.

The geoid is a complex, physically-based surface, and can vary by up to 100 meters in height from a geocentric ellipsoid. Thus, national and regional vertical datums around the world, which are locally tied to MSL, are significantly different from one another when considered on a global basis. In addition, due to the realization and orthometric height approximations of various vertical datums, other departures at the meter level or more will be found when comparing elevations to a global geoid reference.

For the United States, the GEOID99 geoid model as been developed to directly relate ellipsoid heights from the NAD 83 three dimensional datum to the NAVD 88 vertical datum. Comparisons with GPS ellipsoid heights on leveled benchmarks show this conversion can generally be accomplished in the conterminous United States to about 2.5 cm (one sigma).

On a global basis, the Earth Gravitational Model (EGM) 1996 was developed to provide an improved WGS 84 spherical harmonic model of the Earth's gravitational potential. EGM 96 is quoted as accurate to better than one meter in gravity surveyed areas.

Land Maps

As discussed earlier the NAD 83 and the NGVD 88 datums were adopted by Congress as datums for the United States. Depending upon the scale of mapping and the spacing of contour intervals, the older NAD 27 and NGVD 29 datums may be adequate to represent the National Spatial Data Accuracy Standard. Except for the largest map scales, the horizontal components of WGS 84 and NAD 83 may be considered equivalent. Datum transformations are available which relate the NAD 27 and NAD 83 datums, and which relate the NGVD 29 and NAVD 88 datums.

Nautical Charts

As discussed earlier, the NAD 83 and the NGVD 88 datums were adopted by Congress as datums for the United States. On a global basis, the International Hydrographic Organization (IHO) designated the use of the World Geodetic System as the universal datum. Since then, the horizontal features have been based on WGS 84 or in other geodetic reference systems which are compatible, such as NAD 83 or the ITRF combined with the GRS80 ellipsoid.

All vertical features and depths are still defined with respect to tidal surfaces, which may differ in definition from chart to chart. Typically, a low waterline, rather than mean sea level, is adopted as the vertical reference for a chart. Representing depths relative to a low waterline is a conservative approach, since depths below a ship’s keel are so important.

Aeronautical Charts

As discussed earlier the NAD 83 and the NGVD 88 datums were adopted by Congress as datums for the United States. On a global basis, the International Civil Aviation Organization (ICAO) designated the use of the WGS 84 as the universal datum. Since then, the horizontal features have been based on WGS 84 or in other geodetic reference systems which are compatible, such as NAD 83 or the ITRF combined with the GRS80 ellipsoid.

All vertical features and elevations are still determined relative to the local vertical datums, which may vary by a meter or more from a global geoid reference.

Vertical Datums (and the vertical part of 3-D datums)
As discussed in the introduction, vertical datums come in two categories: those based on a form of Mean Sea Level (MSL), which we will call *Orthometric Datums*, and those based on tidally-derived surfaces of high or low water, which we will call *Tidal Datums*. In addition, there is a distinct category of 3-dimensional datums, that are typically realized through space-based systems, such as GPS. We will consider the vertical component of 3-D datums as another type of vertical datum, and refer to these *as 3-D Datums*.

VDatum converts between 26 different vertical datums. There are many other datums used globally, but these are not addressed in this document. The general categories of datums are:

Orthometric Datums

NAVD 88	North American Vertical Datum 1988
NGVD 29	North American GeodeticVertical Datum 1929

Tidal Datums

MLLW	Mean Lower Low Water
MLW	Mean Low Water
LMSL	Local Mean Sea Level
MTL	Mean Tide Level
DTL	Diurnal Tide Level
MHW	Mean High Water
MHHW	Mean Higher High Water

3-D Datums

NAD 83 (86)	North American Datum 1983 (1986)
WGS 84(G873)	World Geodetic System 1984 (G873)
WGS 84(G730)	World Geodetic System 1984 (G730)
WGS 84(orig)	World Geodetic System 1984 (original system -- 1984)
WGS 72	World Geodetic System 1972
ITRF97	International Terrestrial Reference Frame 1997
ITRF96	International Terrestrial Reference Frame 1996
ITRF94	International Terrestrial Reference Frame 1994
ITRF93	International Terrestrial Reference Frame 1993
ITRF92	International Terrestrial Reference Frame 1992
ITRF91	International Terrestrial Reference Frame 1991
ITRF90	International Terrestrial Reference Frame 1990
ITRF89	International Terrestrial Reference Frame 1989
ITRF88	International Terrestrial Reference Frame 1988
SIO/MIT 92	Scripps Institution of Oceanography/Massachusetts Institute of Technology 1992
NEOS 90	National Earth Orientation Service 1990
PNEOS 90	Preliminary National Earth Orientation Service 1990

In practice, a user will only have to transform between a few datums. The 26 varieties of tidal and 3-D datums supported by VDatum are supplied merely to be complete.

Schematic of Selected Vertical Datum Reference Surfaces at Tampa Bay (Approximate – not to scale)

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---------------------------------------------  WGS 84(G873)

---------------------------------------------  NAD 83(86)

               (large offset)

---------------------------------------------  MHHW

---------------------------------------------  MHW

---------------------------------------------  NAVD 88

---------------------------------------------  LMSL

---------------------------------------------  MLW

---------------------------------------------  MLLW
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The separations between the tidal surfaces and the NAD 83 (and other 3-D datums) are in excess of 24 meters. The relation NAD 83 to NAVD 88 is the GEOID99 geoid height model. The relation of NAVD 88 to LMSL is calibrated from tide model comparisons with leveled, tidal benchmarks, and is expressed as a constant 0.163 meters (SST.GTX).

WGS 84, WGS 84 (G730), WGS 84 (G873), and NAD 83 (86)
It is not well known that there is more than one WGS 84 reference frame. To date, there have been three WGS 84 reference frames: WGS 84, WGS 84 (G730), and WGS 84 (G873). In this document, the original WGS 84 frame is denoted WGS 84 (orig.). The dates of these reference frames are:

WGS 84 (G873) -- Broadcast GPS orbit from January 29, 1997 to present.
WGS 84 (G730) -- Broadcast GPS orbit from June 29, 1994 to January 28, 1997.
WGS 84 (orig.) -- Broadcast GPS orbit from January 23, 1987 to June 28, 1994.

The WGS 84 frames were updated to conform with the best available scientific reference frames. One can establish an association:

WGS 84 (G873) -- Equivalent to ITRF94(1997.0) at the few centimeter level.
WGS 84 (G730) -- Equivalent to ITRF92(1994.0) at the few centimeter level.
WGS 84 (orig.) -- Equivalent to NAD 83 (86) within the conterminous US.

The shifts between WGS 84 (orig.) and WGS 84 (G730) [and for NAD 83 (86) to ITRF92(1994.0)] are a little over 2 meters. The shifts between WGS 84 (G730) and WGS 84 (G873)) [and for ITRF92(1994.0) to ITRF94(1997.0)] are just a few centimeters.

The original NAD 83 (86) reference frame has been retained throughout the years, even though that frame is not geocentric by about 2 meters.

This has lead to two seemingly contradictory statements found in literature:

> WGS 84 is identical to NAD 83
> WGS 84 differs from NAD 83 by about 2 meters.

As seen from above, the problem arises because the full datum names have not been used. To be exact:

WGS 84 (original) is identical to NAD 83 (86) (within the conterminous US)
WGS 84 (G873) differs from NAD 83 (86) by about 2 meters.

We can not close this section without emphasizing one final point. It is unlikely that most users will detect differences between WGS 84 (G873) and NAD 83 (86) without rigorous processing. This is due to how one obtains WGS 84 (G873) coordinates and how one obtains NAD 83 (86) coordinates. There is no readily accessible network of WGS 84 (G873) control stations, as compared to the National Spatial Reference System (NSRS) of NAD 83 (86) control stations. So, generally, one uses autonomous GPS (point positioning) methods with code pseudoranges to establish a point in WGS 84 (G873). Broadcast orbits are currently accurate to about 3 meters RMS. An individual code range is generally accurate from a few decimeters to several meters or more, depending upon multipath. With SA off, with atmospheric models, and with nominal atmospheric conditions, pseudorange horizontal accuracy (conterminous US) is about 5 meters (2D -- 95%). So, one can see the *realization* of the WGS 84 (G873) datum is usually at a few meter level, even though the *idealized* WGS 84 (G873) datum is defined at a few centimeter level. By contrast, the NAD 83 system is both *defined* and *realized* at a 5 centimeter level. Such precise realizations are performed with differential carrier phase, not with pseudoranges.

WHAT DATUM IS MY DATA IN? WHAT DATUM DO I WANT?

These are the key questions that need to be answered. A supplier of geospatial data should provide the appropriate metadata, in this case datum identification, to allow its use. If you generate new data, you should provide the datum identification along with those new data.

When dealing with paper maps and charts, the datums are typically provided. Topographic maps (from USGS, for example) will have elevations referenced to either NAVD 88 or to the older NGVD 29. The NAVD 88 was affirmed as the official vertical datum for the United States by a notice in the Federal Register (Vol. 58, No. 120 page 34245) on June 24, 1993. Also, note that maps have a horizontal datum. Even if the features are horizontally referenced to NAD 83, this does not mean the vertical datum is a 3-D vertical datum.

Nautical charts will have depths referred to different tidal surfaces, which may vary from chart to chart. In the United States, MLLW and MLW are the typical low water reference surfaces. Note: to support harbor and river navigation, bridge clearances are typically referenced to a high water, MHW or MHHW; not to a low water. Also note that charts (like maps) have a horizontal datum. Even if the features are horizontally referenced to NAD 83, this does not mean the vertical datum is a 3-D vertical datum.

As discussed above, when collecting data georeferenced with autonomous GPS, then you are in the WGS 84 (G873) datum. Note, however, that data collection systems may provide the option of output in different datums. If you selected such an option, then your data will probably be in the selected datum.

If however, you are collecting data georeferenced by augmented GPS, then you are probably in NAD 83 (86). If the augmentation was one of the U.S. Coast Guard Maritime Differential GPS or National Differential GPS (NDGPS) base stations, then those broadcast pseudorange correctors are established using NAD 83 (86) coordinates, and your output coordinates will be in NAD 83 (86). If you are using National CORS data for carrier phase postprocessing, and if you are processing with ITRF97 coordinates, then your output coordinates will be in ITRF97. Note that there is a whopping 1.5 meter vertical datum difference between NAD 83 (86) and WGS 84 (G873) in the Tampa Bay region (and only about a 1.5 millimeter difference between ITRF97 and WGS 84 (G873) in the Tampa Bay region). As above, augmented GPS data collection systems may provide the option of output in different datums. If you selected such an option, then your data will probably be in the selected datum.

Details on Orthometric Datums

The North American Vertical Datum (NAVD) 1988 is based on an adopted elevation at Point Rimouski (Father's Point). It uses Helmert orthometric heights as an approximation to true orthometric heights. By contrast, the National Geodetic Vertical Datum (NGVD) 1929 was fixed to a set of reference tide gauges, without correction for local sea surface topography departures, and it used normal orthometric heights as an approximation to true orthometric heights. The discrepencies between these two datums is not a simple offset and tilt, but a complex surface that is related to gravity field variations of the Earth. Neither NAVD 88 nor NGVD 29 are in conformance with mean sea level, nor with the geopotential surface that best fits the Earth's mean sea surface (idealized global geoid). NAVD 88 is a better realization of an orthometric datum based on a geopotential surface; however that geopotential is not the ideal global geoid. In addition, one will have average local departures from global mean sea level due to prevailing winds, currents, atmospheric pressure, temperature, and salinity effects. All of these effects are absorbed into an offset between NAVD 88 and mean sea level as established by the Tampa Bay hydrodynamic model. This relation of NAVD 88 to LMSL is calibrated from tide model comparisons with leveled, tidal benchmarks, and is expressed as a constant 0.163 meters.

Details on Tidal Datums

Tidal datums are referenced to stages of the tide at a particular point. At a point we have tidal datums such a Mean Low Water (MLW) and a Mean Lower Low Water (MLLW). Both are referencing a low water, but are computed differently due to the definitions of MLW and MLLW. There are dozens of different definitions of high, low, and mean waters used around the world.

In addition, due to the spatial variability of tidal dynamics, a given low water definition will differ from mean sea level by varying amounts from place to place. The spatial variation of tide dynamics is complex, and depends upon location on the Earth, the 2-D shape of the coast, the bottom hydrography of a bay or harbor, and other effects such as wind, salinity, and river discharge. Establishment of tide zones during the process of data capture and chart compilation addresses tidal spatial variation. The most comprehensive approach to this problem (which was done for Tampa Bay) is to establish tidal datum grids derived from suitable numerical circulation models.

Lower low water --	The lower of the two low waters of any tidal day. The single low water occurring daily during periods when the tide is diurnal is considered to be a lower low water.
Low water --	Minimum height reached by a falling tide.
Higher high water --	The higher of the two high waters of any tidal day. The single high water occurring daily during periods when the tide is diurnal is considered to be a higher high water.
High water --	Maximum height reached by a rising tide.
Diurnal tide level --	The average of mean lower low water and mean higher high water.
Mean tide level --	The average of mean low water and mean high water.
Mean sea level --	Average height of the surface of the sea for all stages of the tide over a 19 year period, usually determined from hourly height readings.

By these definitions, one can envision that mean sea level, mean tide level, and diurnal tide level are all close to one another, that mean lower low water is lower than mean low water, and that mean higher high water is higher than mean high water. The magnitudes of the high and low waters vary from place to place depending upon the range of the tide, that the local mean sea level at a point will vary due to physical effects, and that the entire set of tidal datums will vary relative to an ellipsoid due to geoidal undulations.

Details on 3-D Datums

As discussed above, all 3-D datums (reference system) represent a reference frame (origin, orientation, and scale) combined with an ellipsoid. The GRS80 ellipsoid is used in VDatum for all 3-D datums. The GRS80 ellipsoid parameters are:

Semi-major axis = 6378137 meters	(exact)
Flattening = 1/298.257222101	(derived)
Semi-minor axis = 6356752.3141 meters	(derived)

The WGS 84 ellipsoid is slightly different in flattening:

Semi-major axis = 6378137 meters (exact)	
Flattening = 1/298.257223563	(derived)
Semi-minor axis = 6356752.3142 meters	(derived)

The difference in flattening between these two ellipsoids causes a maximal departure of 0.1 millimeter in ellipsoidal height at the Earth's poles. This difference is considered negligible for VDatum.

The majority of 3-D datums supported by VDatum will not be encountered in practice. They are provided for completeness. ITRF97, for example, is customarily realized through post-processed GPS carrier phase from a National CORS station using an ITRF97 coordinate for that CORS. Most likely, GPS-based georeferencing will be in the NAD 83 (86) datum. Data may be in the WGS 84 (G873) datum if the data were collected through autonomous GPS.

Rigorous nomenclature for 3-D datums requires specification of an epoch date for any ITRFxx coordinate. This is because the ITRF datums include models for plate tectonic motion. Thus, an ITRF97 coordinate for a station at one epoch will differ from the ITRF97 coordinate for the same station at a different epoch. This variation is (generally) avoided with NAD 83 (86) coordinates, since those are anchored to the North American Plate. Exceptions occur with active tectonic areas, such as Southern California, or along the Pacific Coast. Since plate motion is generally horizontal, epoch date differences between measurement and datum reference epochs are neglected.

List of details and epoch dates

NAD 83 (86)	-- Date tag 1986.0. Published by NGS from 1986 to present. Datum is anchored to North American Plate, so epochs only used in crustal motion software. (note: numerous realizations are indicated by date tags, but all retain original 3-D frame.)
WGS 84 (G873)	-- Reference epoch 1997.0. Broadcast GPS orbit from January 29, 1997 to present.
WGS 84 (G730)	-- Reference epoch 1994.0. Broadcast GPS orbit, June 29, 1994 to January 28, 1997.
WGS 84 (orig.)	-- Broadcast GPS orbit from January 23, 1987 to June 28, 1994.
WGS 72	-- Broadcast GPS orbit from start of GPS operations to January 22, 1987.
ITRF97	-- Reference epoch 1997.0. Used in NGS from August 1, 1999 to present. (note: negligible alteration in coodinate realization adopted June 3, 2000.)
ITRF96	-- Reference epoch 1997.0. Used in NGS from March 1, 1998 to July 31, 1999.
ITRF94	-- Reference epoch 1996.0. Used in NGS from June 30, 1996 to February 28, 1998.
ITRF93	-- Reference epoch 1995.0. Used in NGS from January 1, 1995 to June 29, 1996.
ITRF92	-- Reference epoch 1994.0. Used in NGS from January 9, 1994 to December 31, 1994.
ITRF91	-- Reference epoch 1992.6. Used in NGS from December 1, 1993 to January 8, 1994.
ITRF91	-- Reference epoch 1988.0. Used in NGS from August 16, 1992 to December 19, 1992.
ITRF90	-- Reference epoch 1988.0. Not used by NGS.
ITRF89	-- Reference epoch 1988.0. Not used by NGS.
ITRF88	-- Reference epoch 1988.0. Not used by NGS.
SIO/MIT 92	-- Reference epoch 1992.57. Used in NGS, December 20, 1992 to November 30, 1993.
NEOS 90	-- Reference epoch 1988.0. Used in NGS from October 20, 1991 to August 15, 1992.
PNEOS 90	-- Not used by NGS.

RESOURCES

Geoid Models: National Geodetic Survey
http://www.ngs.noaa.gov/GEOID/

The VERTCON PC Software: National Geodetic Survey
http://www.ngs.noaa.gov/PC_PROD/pc_prod.shtml#VERTCON
ftp://ftp.ngs.noaa.gov/pub/pcsoft/vertcon/README.TXT
http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

Reference Frame Transformations (incorporated in HTDP): National Geodetic Survey
http://www.ngs.noaa.gov/PC_PROD/pc_prod.shtml#HTDP
http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.html

Water Level observations and analysis:
Center for Operational Oceanographic Products and Services
http://co-ops.nos.noaa.gov/index.html

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